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Systematic Review

Biomechanical Research Methods Used in Acrobatic Gymnastics: A Systematic Review

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Abstract: The biomechanical analysis of Acrobatic Gymnastics elements has not been extensively explored in scientific research to date. Due to the increased challenge of implementing experimental protocols and collecting data from multiple individuals, it is required to develop strategies that allow a safe, valid and reproducible methodology. This work aims to collect information and systematically analyze the biomechanical approach in Acrobatic Gymnastics to date. A search was conducted in the Web of Science, Scopus, EBSCO, PubMed and ISBS databases. After the selection and quality-control phases, fourteen documents were included. The results revealed that the biomechanical research in Acrobatics has been focused on balance evaluation, in which the force plate and the center of pressure are the most used instrument and variable, respectively. Research has been focused on kinetics evaluation. Kinematics analysis of pair/group elements would provide scientific answers to unresolved problems, considering that Gymnastics provides almost limitless possibilities to study human motion. Researchers should focus on the type of element, difficulty degree, main characteristics, relationship between the instrument and floor surface specificity and safety conditions. We encourage gymnastics clubs and coaches to establish networks with biomechanics laboratories, allowing to bridge the gap between research and practice.

Keywords: acrobatic gymnastics; biomechanics; methods; review

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1. Introduction

Acrobatic Gymnastics, previously known as Sport Acrobatics, was adopted by the Fédération Internationale de Gymnastique (FIG) in 1998, with the overarching goal of uniting all the gymnastics disciplines and for Acrobatics to ultimately become an Olympic sport [1]. Acrobatic gymnasts collaborate in pairs or groups to execute balance and dynamic elements. A considerable proportion of the final competition score is based on the correct execution of pair/group pyramids formed by at least one gymnast in the base of the formation who supports the partner(s) on the top while maintaining static postures for at least three seconds [2].

The mechanisms of maintaining static positions composed of more than one person have not been much explored in scientific research to date, despite its importance to performance [3–5]. The literature has been focused on studying the gymnasts' individual abilities [6–9], due to the increased challenge of implementing experimental protocols and collecting data from multiple individuals. One study has investigated the association between individual abilities and pyramid performance [10]. The implementation of a feasible methodology becomes even more complex when the goal is to evaluate elements with a flight phase, that is, dynamic elements where at least two gymnasts interact with each other [11].

Accordingly, it is required to develop strategies that allow a safe and valid methodology for the biomechanical analysis of pair and group elements of Acrobatic Gymnastics. The ultimate goal would be to implement training protocols to assist coaches in improving techniques and enhancing pair/group performances.

The first step in this direction is to examine the biomechanical research conducted in Acrobatic Gymnastics to find what has been done so far and the features that can be enhanced. Therefore, the aim of this work was to collect information and systematically analyze the biomechanical approach in Acrobatic Gymnastics to date, focusing on (1) sample characterization, (2) the most prevalent research topics and type of analysis within the biomechanics field, (3) instruments, (4) variables selection and assessment, (5) sport specificity and the relevance of the practical implications and (6) the features to be considered when designing a reproducible methodology. This work should provide key tools to enhance the biomechanical scientific research conducted in this sport.

2. Materials and Methods

2.1. Search Strategy and Inclusion Criteria

A systematic review of the available literature was conducted following the PRISMA 2020 statement items for systematic reviews in the sport and exercise medicine, musculoskeletal rehabilitation and sports science fields: the PERSiST (implementing Prisma in Exercise, Rehabilitation, Sport medicine and Sports science) guidelines [12].

A search for documents published up to 30 September 2022 was conducted in the electronic databases of Web of Science (WoS), Scopus, EBSCO, PubMed and the International Society of Biomechanics of Sports (ISBS) using the following search terms: "(acrobatic* AND gymnastic*) AND biomechanic*".

Since Acrobatic Gymnastics is a recent discipline, we did not use any time filter and we did not restrict the document type. The WoS database integrated the results from PubMed. Scopus and Ebsco contained distinct documents and allowed the inclusion of a more comprehensive time window. The Proceedings of the ISBS Conference, as one of the most important Sports Biomechanics meetings, included relevant preliminary work on this topic, such as experimental works through conference abstracts or full-text articles, which increased the number of documents included. The search was conducted in Google Scholar, using a filter to include only the documents published in the ISBS.

A document was included in this review if its participants were Acrobatic gymnasts, it applied biomechanical assessment methods and if it was written in English, Portuguese or Spanish. Documents were excluded if they referred to studies regarding other gymnastics disciplines.

2.2. Quality Control Assessment

As recommended in Faber et al. [13], the overall methodological quality of the studies was assessed using critical review forms [14] to evaluate the following 16 items: (1) study purpose, (2) relevance of background literature, (3) appropriateness of the study design, (4) sample description, (5) sample size, (6) informed consent procedure, (7) outcome measures, (8) validity of measures, (9) details of the intervention procedure, (10) significance of results, (11) analysis, (12) importance for practice, (13) description of drop-outs, (14) conclusion, (15) practical implications and (16) limitations.

Each item was classified as 1 (meets criteria), 0 (does not fully meet the criteria) or NA (not applicable). For each document, a final score expressed as a percentage was calculated by following the scoring guidelines [13]. This final score corresponded to the sum of every score in each article divided by 16. The documents were classified as follows: (1) low methodological quality, score $\leq$50%; (2) good methodological quality, score between 51 and 75%; and (3) excellent methodological quality, score >75% [13,15]. Any document that scored below the cut-off quality threshold ($\leq$50%) established for this review was excluded [16]. Two reviewers (IL, LAC) assessed the studies' illegibility. When the decision to include or exclude a given article was not unanimous, a third reviewer (MG) made the final decision. Relevant data were extracted from each document by one author and verified by two others.

3. Results

3.1. Search, Selection and Inclusion of Publications

The document illegibility process is depicted in Figure 1. One hundred and six references were downloaded to Endnote X20 (Clarivate Analytics, Philadelphia, PA, USA), where 21 duplicates were automatically identified and removed. Then, 85 titles and abstracts were screened and 32 were selected, that is, 53 non-related titles and abstracts were removed. These 32 full-text documents were manually analyzed to select only the articles about Acrobatic Gymnastics using any biomechanical approach. In this process, 21 documents were excluded, leaving 11 eligible documents. Four additional documents were identified via citation searching and included in the review after being assessed for eligibility, leading to a grand total of 15 documents included in the review.

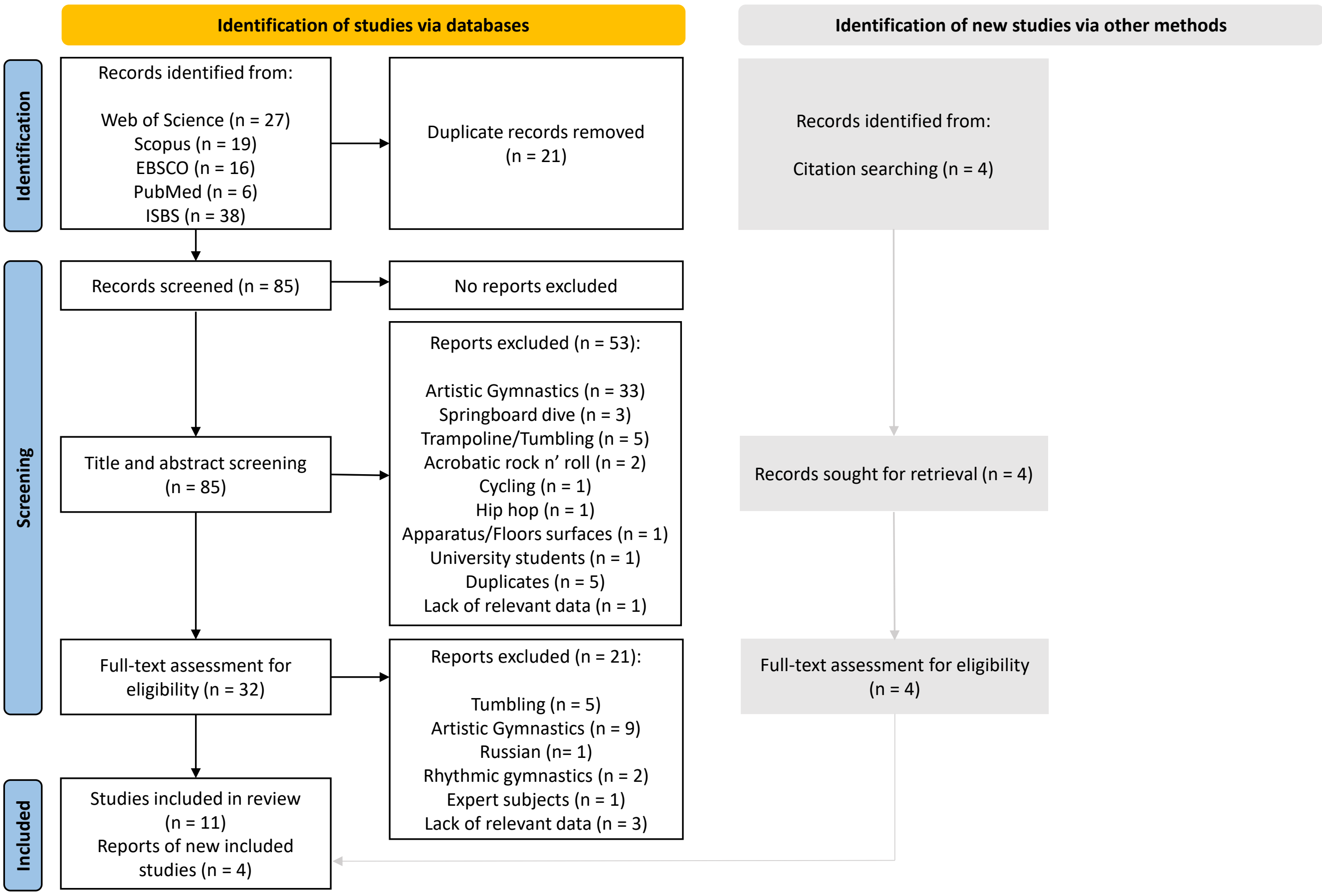

Figure 1. Document identification, screening and illegibility process.

The main exclusion factor was documents containing data from other gymnastics disciplines, namely, Artistic Gymnastics, Springboard Dive, Tumbling or Trampoline. There were also three documents lacking relevant data, that is, they had insufficient information to fill, or accurately calculate, the necessary parameters for inclusion in the review.

3.2. Quality of the Studies

Table 1 reports the results from the quality-control assessment of each document. The most noteworthy results were that (1) two publications achieved the maximum score of 100%; (2) eleven studies presented excellent methodological quality; (3) three were classified as having good methodological quality and (4) the mean score for the 12 selected studies was 80.87%. The right column describes how many times a specific item was not reported in an included document. Thirteen articles did not justify the sample size, five did not acknowledge and describe the study limitations and four did not report the results in terms of statistical significance or the implications for practice given by the study results. Forty-three items were not reported, corresponding to 18% of the total criteria required.

Table 1. Results from the quality control assessment of the documents included in the review (n = 15).

Question	Floria and Harrison [17]	Opala-Berdzik et al. [7]	Sobera et al. [18]	Opala-Berdzik et al. [8]	Gómez-Landero et al. [6]	Boloban and Mistulova [19]	Floría et al. [3]	Ivanov and Kuleva [4]	Leal del Ojo et al. [5]	Bradley et al. [11]	Paulino et al. [20]	Vernetta-Santana et al. [9]	Floría et al. [21]	da Silva et al. [22]	Leal Del Ojo et al. [10]	Total Items Not Reported
Was the study purpose stated clearly?	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1
Was relevant background literature reviewed?	1	1	1	1	1	0	1	0	1	1	1	1	0	1	1	3
Was the design appropriate for the research question?	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Was the sample described in detail?	1	1	1	1	1	0	1	0	1	0	1	1	1	1	1	3
Was the sample size justified?	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	13
Was informed consent obtained? **	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	2
Were the outcome measures reliable?	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
Were the outcome measures valid?	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
Were the methods described in detail?	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
Were results reported in terms of statistical significance?	0	1	1	1	1	0	1	1	1	0	1	1	0	1	1	4
Were the analysis methods appropriate?	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
Was the importance for practice reported?	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	3
Were any drop-outs reported?	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	NA	1
Were conclusions appropriate given the study methods?	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Are there any implications for practice given in the study results?	0	0	0	1	1	0	1	1	1	1	1	1	1	1	1	4
Were study limitations acknowledged and described?	0	1	0	1	1	0	1	0	1	0	1	1	1	1	1	5
Total Score	10	13	12	14	14	3	15	9	15	11	14	13	12	14	14	43
Percentage (%)	66	87	80	93	93	20	100	60	100	73	93	87	80	88	93	18
Classification	G	E	E	E	E	L	E	G	E	G	E	E	E	E	E	-

1 = yes; 0 = no; NA = not applicable; ** (if not described, assume no; if not applicable, assume NA); L = low methodological quality, score $\leq$ 50%; G = good methodological quality, score between 51 and 75%; and E = excellent methodological quality, score > 75%.

After the quality assessment, one article was excluded from further analysis, as its low methodological quality of 20% was below the cut-off quality score threshold (≤50%) established for this review [15].

3.3. General Description of the Documents

Table 2 provides a general description of the 14 documents included in the review, including information regarding the (1) sample; (2) instruments; (3) variables selection and assessment; (4) type of analysis within the biomechanics field and (5) main conclusions. Table 2 is divided into three types of documents, depending on whether they were concerned with individuals, pyramids or an assorted analysis.

Table 2 shows that 10 documents investigated the balance in Acrobatic Gymnastics, either of individual gymnasts, such as during standing [7,8], handstand [18] and headstand [6], or from pair pyramids [3–5,21]. Others investigated whether pyramid performance was determined by the individual gymnasts' balance [10]; the fatigue effects on postural steadiness and electromyography (EMG) modulation during unipedal stance [22]; and the kinematic analysis of a dynamic element from pairs [11].

Regarding the sample, documents included only females (n = 8), males (n = 2), both sexes (n = 3) or did not specify the sex (n = 1). Gymnasts competing at national (n = 6) or both national and international level (n = 1) were included, in which analysis of pairs or individuals was the most frequent. Studies described the training experience [18] or the weekly training frequency [17] for performance level characterization. Three documents did not specify the skill level and the remaining (n = 2) did not provide enough information for comparison. The sample size ranged from 4 to 46 participants. The gymnasts' age ranged from 6 to 20 years old, including base and top gymnasts [3,5,6,10,11,20,21], adults acting as base gymnasts [9] and those without a role specification [7,17,18,22].

Table 2 shows that kinetics analysis (n = 11) was the most common biomechanical approach. Other approaches (kinematics, plantar pressure analysis, tensiomyography and EMG) were observed just once. The most common biomechanical instrument was the force plate, with 11 documents presenting postural studies evaluating the center of pressure (CoP). The most common CoP parameters used to investigate the pyramid balance were the path length, mean velocity and surface area. The vertical ground reaction force (GRF) [17,18] and inter-trial variability measurements [5,21] have also been reported. One study used inertial measurement units (IMU, XSens Inertial system) to measure angular kinematics [11]. One study used a plantar pressure system (Pedar Mobile® system) [20]. Another study used tensiomyography (Furlan & Co., Ltd., Manchester, UK) for neuromuscular response and recovery time assessment [9]. EMG was combined with kinetics analysis to investigate whether neuromuscular adaptation due to training would lead to different behavior of CoP and EMG quantifiers after fatigue [22].

Among the most relevant conclusions from these studies, we can enumerate the following: (1) the influence of the range of motion (rather than GRF improvement) in enhancing childrens' vertical jumping performance [17]; (2) the relation between postural stability and discipline-specific training experience and anthropometric traits, reported by the effect of visual cues, experience level, body mass, BMI [7,8] and age [6] on postural steadiness; (3) specific test recommendations, such as the unipedal stance for base gymnasts [6] or the CoP displacement during headstand performance in top gymnasts as a test to predict better scores in the handstand pyramid [10]; (4) the landing surfaces and plantar pressure reduction using mattresses during training to prevent injuries [20]; (5) the fatigability profile, the identification of optimal recovery periods and training planning according to the enhancement levels [9]; and (6) the different neuromuscular control strategies used by expert Acrobatic gymnasts (as compared to healthy untrained matched controls) to keep their postures during single-legged quiet standing after a fatiguing protocol [22].

Table 2. General description of the sample, material and methods and main conclusions from the documents included in the review (n = 14).

Author (Year)	Sample					Material and Methods				Type of Analysis	Variables	Main Conclusions
	n	Groups	Age (SD)	Sex (*n*)	Level	Test	Trial (*n*)	Instrument	Rest (min)			
Individual analysis												
Floria and Harrison (2011) [17]	36	-	6.5 (0.9)	F	-	CMJ	3	Force plate	2	Kinetics	CoM flight height and vertical displacement Average vertical GRF	Children can enhance their vertical jumping performance by increasing the ROM rather than improving the GRF or their application.
Opala-Berdzik et al. (2018) [7]	28	G: 15 N-A: 13	Range: 10–13	F	Nat.	QS	2	Force plate	1	Kinetics	CoP mean velocity (AP and ML)	Acrobatic gymnasts did not make use of their trained abilities. Heavier gymnasts might have been more stable than lighter ones during quiet standing.
Sobera et al. (2019) [18]	8	LE: 4 ME: 4	22.5 (2.5) 27.0 (4.9)	M	-	HandS	5	2 force plates (one hand on each)	-	Kinetics	CoP amplitude GRF (vertical, ML, AP). Frequency index	ME: less variation and lower frequency of body sway. The right hand works as the main support, while the left performs balance control movements (can be due to right-hand dominance).
Opala-Berdzik et al. (2021) [8]	30	T: 10 Artistic: 10 N-A: 10	Range: 10–13	F	Nat.	QS	4	Force plate	1	Kinetics	CoP mean velocity (AP and ML)	Greater body mass and BMI gives better postural steadiness. Relationships between postural steadiness and discipline-specific training experience and anthropometric traits.

Table 2. *Cont.*

Author (Year)	Sample					Material and Methods				Type of Analysis	Variables	Main Conclusions
	n	Groups	Age (SD)	Sex (*n*)	Level	Test	Trial (*n*)	Instrument	Rest (min)			
Gómez-Landero et al. (2021) [6]	46	Early B: 6 Early T: 18 Mid-B: 17 Mid-T: 5	Range: 10–18	F (37) M (9)	Nat.	US HeadS	6	Force plate	2	Kinetics	CoP total length (AP and ML) and mean speed	An effect of age on static balance, regardless of height, role and test. Mid-adolescents had better balance control than early adolescents. Age groups should be considered during training, evaluation and selection.
Pyramid analysis												
Floría et al. (2015) [3]	16	B: 8 T: 8	B: 13.5 (0.9) T: 10.0 (1.1)	F	Nat.	P P	10	2 force plates	2–3	Kinetics	CoP: Path length, variance, range trajectory and surface area of each foot	Link between pyramid stability measures and acrobatic gymnastic performance. Distinct functions of each leg to maintain balance. Asymmetric foot positions might improve the pyramid balance.
Floría et al. (2015) [21]	12	B: 6 T: 6	B: 13.5 (0.9) T: 10.0 (1.1)	F	-	P Judges score	5	2 force plates (one foot on each)	2–3	Kinetics	CoP path length of each foot	Lower intratrial variability in the CoP path length in pyramid execution is associated with higher scores.
Ivanov and Kuleva (2019) [4]	12	-	15 (3)	F	-	US, QS, HandS P P	12	Force plate	-	Kinetics	CoP trajectories Ellipse area CG TPL	Balance stability (CoP ellipse area + total path length) differs significantly: the CoP ellipse area is lower and TPL longer with eyes closed.

Table 2. *Cont.*

Author (Year)	Sample					Material and Methods				Type of Analysis	Variables	Main Conclusions
	n	Groups	Age (SD)	Sex (*n*)	Level	Test	Trial (*n*)	Instrument	Rest (min)			
Leal del Ojo et al. (2022) [5]	47	B: 22 T: 25 Pairs: 25	B: 17 (3) T: 11 (2)	F (34) M (13)	Nat.	P P P Judges score	15	Force plate	2–3	Kinetics	CoP displacement (ML and AP) Range trajectory CoP area	Higher CoP excursions and intertrial variability in the high difficulty pyramid. Higher judges' scores were associated with lower CoP excursions in all the pyramids. There is a clear effect of the pyramid's degree of difficulty on the CoP excursion.
Bradley et al. (2020) [11]	4	B: 2 T: 2 Pairs: 2	Range: 8–17	-	LE ME	Back somersault from base's shoulders	3	XSens Inertial system	2	Kinematics	Duration of each phase Peak joint angle	ME: greater knee flexion, increased ROM (take-off) and adduction/abduction (arm swing). LE: higher shoulder flex/extension and internal/external rotation (preparation and take-off). Training should focus on developing temporal movement efficiency.
Assorted analysis												
Paulino et al. (2021) [20]	6	B: 3 T: 3	B: 16 T: 12	F	-	J from 0.45 m J from 1.15 m	30	Plantar pressure insoles	1	Plantar pressure evaluation	Symmetry index Highest pressure Average pressure	Mattresses significantly reduced the plantar pressure. They can be used during training to avoid the occurrence of injuries.

Table 2. *Cont.*

Author (Year)	Sample					Material and Methods				Type of Analysis	Variables	Main Conclusions
	n	Groups	Age (SD)	Sex (*n*)	Level	Test	Trial (*n*)	Instrument	Rest (min)			
Vernetta-Santana et al. (2018) [9]	11	B	20.8 (3.2)	M	Nat. Int.	Forward somersaults from 60 cm	12	Tensiomyography sensor	2	Tensiomyography	Muscle belly radial displacement Contraction and delay time Muscular response speed	The fatigability profile may help identifying optimal recovery periods and training planning according to the enhancement levels. To perform at the end of the session, or if in the middle, not to exceed 5–15 min between the plyometrics and the other exercises.
da Silva et al. (2022) [22]	28	G: 14 N-A: 14	G: 16.1 (3.1) N-A: 16.3 (3.2)	F	G: Nat.	US Standing isometric plantarflexion	10	Force plate Surface sEMG	2	Kinetics sEMG	CoP area, RMS, mean velocity, power spectrum sEMG signal amplitude and median frequency	Fatigue increased ML oscillations. sEMG: expert G used distinct neuromuscular control strategies when fatigued. The design of gymnastics training might consider strategies to improve specific muscles performance for which activation patterns were used.
Leal Del Ojo et al. (2022) [10]	40	B: 20 T: 20	B: 16.5 (2.8) T: 11.3 (1.7)	F (28) M (12)	Nat.	US HS P Judges score	9	Force plate	2	Kinetics	CoP path length (AP and ML) Surface area Mean speed	T: higher pyramid performance associated with better headstand balance. B: US was not associated with pyramid performance. CoP displacement during headstands could help coaches and gymnasts to assess the handstand pyramid performance.

Legend: AP—anteroposterior; B—base gymnast; BMI—body mass index; CoP—center of pressure; CoG—center of gravity; CMJ—counter movement jump; CoM—center of mass; F—female; GRF—ground reaction force; G—gymnast; HANDS—handstand; HEADS—headstand; Int.—international; LE—less experienced; M—male; ML—medial lateral; ME—more experienced; N-A—non-athletes; Nat.—national; P—pyramid; QS—quiet standing; ROM—range of motion; sEMG—surface electromyography; T—top gymnast; US—unipedal stance.

In pair/group elements, static balance evaluation using CoP provides quick and accurate information about pyramid performance, allowing coaches to select less unstable pyramids, leading to better scores [5]. Regarding dynamic elements, training should focus on developing temporal movement efficiency to enhance the effective progression of acrobatic gymnasts [11].

4. Discussion

This work aimed to systematically review the biomechanical research in Acrobatic Gymnastics to understand the features that can be enhanced. Therefore, this discussion is divided into distinct aspects: (1) sample characterization, (2) research topics within the biomechanics field and tests recommendations, (3) instruments, (4) variables selection and assessment, (5) sport specificity and the relevance of the practical implications and (6) limitations.

4.1. Sample Characterization

Acrobatic gymnasts are either base or top gymnasts. According to their position, training and competitive matters are distinct; therefore, such information should be described in studies. Moreover, since pairs/groups can be formed by different compositions of female and male athletes, separate base and top descriptions would improve the information available for Acrobatic Gymnastics.

In our results, participants were national or international athletes or defined as "novice and experienced" [11], which did not provide a precise description for data comparison. One study included state championships, national league or higher-level competitors (e.g., pan American and world class) [22]. An accurate sample characterization is an important methodological aspect, clearly detailing, beyond anthropometric measures, the following characteristics: (1) the roles included when assessing individual gymnasts' abilities, since the analysis can be focused only on top gymnasts' [8] or base gymnasts' traits [9]; (2) the age group (youth, 11–16, 12–18, junior elite and senior elite); (3) the official competition categories (mixed, men's or women's pairs and men's or women's groups); and (4) titles achieved (if applicable). Although some studies provided a clear characterization, the gymnasts' age group and competition categories descriptions were missing. For instance, Leal del Ojo et al. [5] evaluated 47 gymnasts (34 females and 13 males), forming 25 national level pairs. The bases were reported as being 17 $\pm$ 3 years old and the tops 11 $\pm$ 2 years old. Since Acrobatic Gymnastics is formed by three pair categories, namely, women's pairs, men's pairs and mixed pairs, it is important to clarify the categories evaluated. In a mixed sample there are diverse possible combinations, and these should be considered in the results interpretation and discussion. For instance, knowing if a pair is female–female is important as there are some parameters (height, abdominal circumference, fat percentage, biiliocristal diameter) that can be used as predictors of performance, predisposing female bases to work in pairs rather than in groups [23]. Proportionality indices also showed that all gymnasts obtained negative body mass values, except the mixed-pair bases [23].

4.2. Research Topics within Biomechanics Field and Tests Recommendations

In Acrobatic Gymnastics, three major routines are developed in pairs or groups, namely, balance, dynamic, and their combination. CoP and CoG are the major biomechanical variables measured to understand postural control in standing tasks. For dynamic exercises, motion analysis to measure the kinematics is the most common approach. Although research on individual elements in Artistic or Acrobatic Gymnastics [6] is important, their transference to pyramid performance is uncertain. For instance, the unipedal stance (with open or closed eyes) was recommended as a valid test to select (talent identification during early specialization) or to evaluate and detect high performance base gymnasts [6]. However, one study found that the higher 'handstand on bent elbows' pyramid performance, the better headstand balance capacity in the top gymnasts, but the base gymnasts' unipedal static balance was not associated with better pyramid performance [10]. For such pyramids, these authors suggested a balance test standing on both legs while balancing a rigid load with its center of gravity higher than its base of support.

Each pyramid has its own requirements, demanding specific tests. Although the headstand balance test in top gymnasts could be used to predict scores in the handstand pyramid, more research is needed to find individual tests (e.g., handstand on unstable supports) with a greater capacity to discriminate between different skill levels and, therefore, determine additional variables associated with the pyramid's performance [10]. For children selection in Gymnastics disciplines (considering their somatotype), a study recommended the use of posturography and more objective techniques, such as dual energy X-ray absorptiometry, anthropometry or bioimpedance, and tasks which are discipline-specific and have the potential to provide valid outcomes, concluding that a child's somatotype/anthropometric characteristics may be a key factor when choosing a particular gymnastic discipline [8]. Information concerning the anthropometric profile of each gymnast provides a reference frame for coaches to improve talent detection and identification, the assignment of a specific role in the sport and, therefore, helps improve athletic performance and injury prevention [23,24].

Most studies have analyzed balance pyramids formed by only one base and one top gymnast [3–5,10]. Although it is possible to have them formed by three or four elements in total, no documents were found for more than pairs (i.e., analyzing group performance), due to the increased challenge of implementing experimental protocols and collecting data from multiple individuals. As such, we recommend the inclusion of groups in upcoming investigations to explore this specificity.

For dynamic exercises, only one study measured the kinematics of a backward somersault, comparing experienced and novice acrobatic gymnasts [11]. The experienced gymnast produced larger knee movements in the take-off phase and a greater adduction/abduction movement during the arm swing during the somersault, while the novice gymnast produced larger shoulder movements during the preparation and take-off phases. There was no information about the dynamic coupling between base and top gymnasts, and how such coupling affects balance and dynamic elements.

4.3. Instruments, Variables Selection and Assessment

The most used instrument and variable in Acrobatic Gymnastics is the force platform and CoP, respectively. Several variables can be calculated from the CoP to study postural control [25]. For pyramid balance evaluation, the main CoP measures computed are (1) CoP amplitude from both or each foot on a force plate [3]; (2) CoP variance to estimate the pyramid stability [3]; (3) the range of ML (medial–lateral) and AP (anteroposterior) CoP displacement [3,5]; (4) CoP area [3,5]; and (5) the bilateral distribution of body weight [3].

Balance studies are usually developed with one or two force plates. By using a single force plate, the understanding of balance control concerns how postural sway changes in both directions (AP and ML) [26], and how it associates with the center of gravity (CoG) [27] or with the limits of the basis of support [28]. Winter [29] argued that feet placement in quiet standing should affect CoP; therefore, to improve the understanding of balance control, he proposed to use two force plates and evaluated different feet positions [30–32]. Duarte and Zatsiorsky [33] discussed what happens when feet are free to stay and move on the force plate, describing the CoP migration patterns. Since these studies, diverse approaches were used regarding the number of force plates and foot placement. One study aimed to assess each limb behavior during two pyramids using two force plates (one foot in each), considering the CoPnet as the weighted sum of CoPleft and CoPright [3,29], as presented below:

$$CoP_{net} = CoP_{left}\ (Fz_{left}/Fz_{left} + Fz_{right}) + CoP_{right}\ (Fz_{right}/Fz_{leftl} + Fz_{right}), \quad (1)$$

where Fz_{left} and Fz_{right} are the vertical GRF of the left and right foot, respectively. When only one foot was on the ground, the CoP was within that foot's plantar surface; if both feet were in contact with the ground, the CoP was somewhere within the basis of support, depending on the position of the vertical projection of the CoG, the relative weight on each foot and their position [29]. To distinguish the CoP measured from a force plate and the CoP calculated from two force plates, CoP_{net} can be defined according to Equation (1) [29]. Thus, by using two forces plates, three sources of information to understand balance control are available: right and left CoP and CoP_{net}. [29]. Accordingly, only analyzing the CoP_{net} area has a methodological limitation: missing how AP and ML sways change, as Equation (1) suggests that the only mechanism that links right and left postural sways is weight transfer.

CoP is a representation of postural sway, and to accurately represent its trajectory we need to consider its bidimensional features. For instance, while using an AMTI force plate, a study calculated the CoP position in the AP and ML directions using the following equation [25]:

$$CoP_{AP} = (-h \times Fx - My)/Fz \text{ and } CoP_{ML} = (-h \times Fy + Mx)/Fz, \quad (2)$$

where h is the height of the base of support above the force plate, for example, a carpet placed over the force plate; Fx, Fy and Fz are the three force components (x, y, and z are the AP, ML and vertical directions, respectively), and Mx, My, and Mz are the three components of the moment of force (or torque) acting on the plate [25]. When feet lie in non-symmetrical positions, GRF and moment of forces may not have the same mechanical participation in balance control during standing. Winter showed that different feet positions can highlight how AP and ML postural sways are controlled [29]. Therefore, to evaluate more complex standing postures, such as the pyramid, using just one force platform will miss important postural sway information. Two studies performed pyramids, positioning both feet on a single force plate to investigate how the CoP excursion and its associated inter-trial variability relate to pyramid performance [5] and whether acrobatic pyramid performance was determined by the individual gymnast's balance [10]. Even when foot position was not controlled or specified during a simple or complex quiet standing, AP and ML postural sways are managing the balance demands induced by CoG displacement. According to the hypothesis to test and the gymnasts' safety, the number of force plates used should be carefully chosen. Placing two feet on one force platform allows an accurate estimate of the AP oscillations [29] when the feet are positioned symmetrically in the sagittal plane. In pyramid balance assessment, this setup facilitates the CoP recording, allowing a simplification of the data analysis process and using fewer calculations [5], given that the dimensions are sufficient to allow all tasks to be conducted comfortably [10].

If the investigation focuses on each limb's behavior, one foot in each platform should be used and the net, right and left AP and ML sways should be considered. Acrobatic gymnasts maintain the pyramid's balance using a different role for each foot, which has implications for coaches when they give feedback on the correct position of each foot and for base gymnasts [3]. However, Leal del Ojo et al. [5] did not control for the foot placement to ensure that the specific stabilization strategies of each gymnast were not limited and because a greater stability was observed when the participants were allowed a self-selected foot placement compared to an imposed placement [34]. Although an asymmetrical feet position facilitates different postural control strategies for each lower limb, further studies are needed to decide the instructions that should be given on foot placement [5].

While 'postural sway' [7,8] represents how postural control manages the body position to balance the CoG [29], its displacement is defined as body sway. In quiet standing, an ankle strategy applies only in the AP direction, under the control of the ankle plantar dorsiflexors, and a separate hip load/unload strategy by the hip abductors/adductors is the totally dominant defense in the M/L direction when standing with feet side by side; for this, the inverted pendulum model gives an understanding of the separate roles of the two mechanisms during critical unbalancing and rebalancing periods [29]. Ankle and hip strategies highlight the potential contribution of EMG analysis in pyramid balance evaluation. The CoP location under each foot is a direct reflection of the neural control of the ankle muscles—increasing the plantar flexor activity moves the CoP anteriorly, while increasing invertor activity moves it laterally net result of the neuromuscular control was CoP_{net}, which reflects the combined control of both the left and right dorsiflexors and plantar flexors [29].

4.4. Sport Specificity and the Relevance of the Practical Implications

Gymnastics disciplines have a high training volume. The fatigability profile obtained in the muscle groups evaluated using tensiomyography as well as the optimal recovery periods identification [9] provide valuable information for training. EMG analysis could provide supplementary information to understand fatigue in Gymnastics. Particularly, in Rhythmic Gymnastics, core strength training improved the body composition (trunk lean mass (mean differences (MD) = −0.31; p = 0.040), lean mass (MD = 0.43; p = 0.037) and bone mass (MD = −0.06; $p < 0.001$) and trunk strength, and increased the muscle electromyographic activity [35], which could improve performance in competitive exercises. In Artistic Gymnastics, the comparison of muscle activity during handstand using different apparatus suggests that each apparatus led to a specific muscle activation, depending on hand support conditions, which alternated the primary wrist strategy and the activation of other muscles controlling balance [36].

One study employed EMG in Acrobatic Gymnastics (combined with kinetics analysis), concluding that the design of Gymnastics training should consider strategies to improve specific muscles' performance (i.e., tibialis anterior, soleus, biceps femoris, spinal erector) for which activation patterns were used by the Acrobatic gymnasts to control single-legged quiet standing [22]. In Acrobatics, the base gymnasts are the "apparatus", providing a platform for the tops to launch from and land on, and to perform either static or dynamic elements, such as the aerial somersault motion. Considering a specific muscle activation for each apparatus, depending on hand support conditions [36] and that both parts (base and top gymnasts) are not as stable as a static apparatus (i.e., the parallel bars or the vault), gymnasts must adapt their technique to each other's constraints. Further studies using EMG analysis during pyramid execution should provide crucial information regarding these mechanisms, aiming to improve performance.

Regarding data comparisons, all the documents that assessed CoP mean velocity found significant differences in height between groups [6–8], which is a clear effect of the specific roles performed by each gymnast (base and top gymnasts) and age groups to which the pair/group belonged. Consequently, this variable has been normalized relative to body height, which is a valid strategy that should be employed in similar situations since it allows a comparison of data across multiple roles and age groups.

While the use of force plates is the gold standard to measure GRF and calculate CoP in static elements, the analysis of elements with a flight phase (dynamic elements) requires a more complex approach not only to ensure gymnasts' safety, but also to consider the floor surface specificity. The competitive routines in Acrobatic Gymnastics, as well as in Artistic Gymnastics, are executed in a spring floor. Depending on the height and type of landing surface, different force magnitudes might be developed, representing an external force that the gymnasts must absorb, such as a soft mat that promotes higher deformations and absorbs more energy; nevertheless, the capability of the Acrobatic gymnasts to absorb energy during the landing is also important to keep balance and not move the feet [20]. Since the musculoskeletal stiffness regulates the storage and reuse of this elastic energy and gymnasts modulate total body stiffness in response to different landing conditions [37], training prepares gymnasts to perform the individual/group elements, including the landing phase. The exposure to high loadings, especially when they jump from high heights and the mechanisms used to absorb the external loading at landings are modified according to the landing surface's stiffness [38]. While Acrobatic gymnasts may be able to adapt their technique to perform static pyramids on a hard surface, when the goal is to analyze dynamic elements with a flight phase, researchers must ensure the surface specificity so that the pair/group does not vary their usual technique and is able to execute the element safely. To understand the performance in a flight phase, motion analysis based on kinematics is necessary.

Research has been focused on kinetics evaluation from pairs (11 documents out of 14). Kinematics analysis of pairs and groups elements would help to provide scientific answers to unresolved problems considering the almost limitless possibilities that Gymnastics provides for the study of human motion, although skill selection for a study can be challenging [39]. Numerous studies are required to understand the nature and complexity of a single skill. However, by acknowledging that every study makes a contribution, sound experimental protocols would make every contribution greater [39]. For instance, Biomechanics studies may assist in finding proper answers in the following aspects: (1) understanding existing techniques; (2) new skill development; (3) increasing safety; (4) equipment design or modification; and (5) athlete–apparatus interaction [40]. In Acrobatics, there are athlete(s)–athlete(s) interactions. Descriptive studies of Gymnastics skills should continue to be undertaken: description is key to understand and analyze motion and is the first step towards skill simulations [39].

4.5. Limitations

This review, like Bradley et al. [11], indicated that little focus has been afforded to Acrobatic Gymnastics kinematics, especially in comparison to Tumbling and Artistic disciplines. Additionally, the main exclusion factor in the document illegibility process of this review was documents containing data from other Gymnastics disciplines, namely, Artistic Gymnastics, Springboard Dive, Tumbling or Trampoline, although the term "Acrobatic Gymnastics" is often applied. This is further hindered by a misunderstanding in the literature with articles stating the focus was on Acrobatic Gymnastics [41] that are Artistic in nature [11]. Future investigations should clearly define the Gymnastics discipline explored, since they are completely distinct from each other.

For the quality-control process, we identified that 13 articles did not justify the sample size, which can be easily solved by conducting a G*Power analysis or stating that all the gymnasts available at the time were recruited. By not providing any type of justification, it gives the idea that more gymnasts could, or should, have participated. The other items were missing more often (i.e., the report of statistical significance, implications for practice and an acknowledgement and description of the limitations), which are mandatory aspects in numerous scientific journals in the submission process. The peer review process should pay close attention to these details to guide future investigations.

The introduction to experimental works using innovative instruments, such as inertial measurement units [11], is a pioneering methodology to conduct a whole-body joint angular kinematics analysis of Acrobatic Gymnastics elements that are either static or dynamic, while multiple subjects interact with each other. This approach presented some limitations, including that the kinematic data were collected only from the top gymnast while secured in a safety harness, which may have affected the habitual technique. Additionally, 3D motion capture systems may provide a great deal of information in terms of kinematics evaluation and EMG analysis regarding muscular activity. This type of equipment would only be available in a laboratory setting in view of the financial investment required, considering that commercial force plates are, by themselves, expensive instruments (about USD 20,000 in the United States) [25]. Fortunately, some Gymnastics clubs or coaches have established networks with Biomechanics laboratories, which allows them to implement more advanced analyses and obtain information to aid the training process, consisting of the necessary evolution of the professional and elite sporting environment to bridge the gap between research and practice [42].

5. Conclusions

While Acrobatic Gymnastics is a modern Gymnastics discipline with a scarce development in scientific research, this systematic review on the biomechanical research conducted in this sport provides relevant practical implications aiming to guide future investigations.

The implementation of reproducible protocols aiming to conduct biomechanical analysis regarding the interaction between multiple subjects, while ensuring gymnasts' safety, is a complex task. In brief, researchers should focus on the type of element (static or dynamic), degree of difficulty, main characteristics (initial and final positions), relationship between the instrument and floor surface specificity and the safety conditions. In the data analysis phase, the following aspects are key to ensure valid measures and a reproducible methodology: a clear definition of the investigation variables, the equations/formulas used and the calculation strategy (step by step), while detailing the main characteristics, such as the components assessed.

Considering that Gymnastics provides almost limitless possibilities for the study of human motion and with the acknowledgement that every study makes a contribution [39], we believe that kinematics analysis of pair and group elements would help to provide scientific answers to unresolved problems. A comparison between novice and experienced gymnasts is a step forward to producing more biomechanical research regarding static positions or elements with a flight phase, allowing the identification of variables that discriminate between various performance levels. Research to find individual tests may also aid in this process and, therefore, determine additional variables associated with the final performance of pyramids.

Our hope is that this systematic review inspires researchers to investigate more and to use more advanced and valid methodologies and instruments. We also encourage Gymnastics clubs and coaches to establish networks with Biomechanics laboratories, which would allow them to develop more advanced analyses and obtain information to aid the training process, bridging the gap between research and practice. This work may help other researchers and academic scholars to understand the features lacking improvement, representing a step forward to enhance biomechanical research in Acrobatic Gymnastics.

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